LA-UR -91-2416

TITLE: **EXPERIMENTAL PROSPECTS FOR OBSERVING FAMILY-NUMBER VIOLATING DECAYS**

AUTHOR(S): *Martin D. Cooper*

DISCLAIMER

AUG 0 1991

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

LosAlamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

EXPERIMENTAL PROSPECTS FOR OBSERVING FAMILY-NUMBER VIOLATING DECAYS*

MARTIN D. COOPER

Los Alamos National Laboratory, Los Alamos, NM 87544

ABSTRACT

A number of the motivations for experimentalists to undertake experiments that test family-number conservation are discussed. A set of principles for experimental design are stated and illustrated with the example of the MEGA experiment at LAMPF. The current status and anticipated prospects for the field are reviewed.

1. Introduction

The search for family violating decays remains an active and exciting area of experimental particle physics. The interest stems from three facts. None of these decays has ever been seen, leading to an experimentally observed conservation of family number for which there is neither a reason nor understanding. Secondly, the minimal Standard Model of electroweak interactions, with massless neutrinos, forbids these decays. Hence, the observation of these decays immediately signals new physics beyond the Standard Model. Finally, in an experimentally clean environment, the observation of one of these decays is free of any physics backgrounds that must be theoretically accounted for to establish the effect.

This paper is divided into three parts. The opening section will give an experimentalist's view of the motivation for searching for these rare decays. The middle section will give a number of common principles employed in carrying out these searches, illustrated with examples from my own work on the MEGA experiment[1] at LAMPF. The closing section will be a survey of recent and planned experiments.

2. Family-Number Violating Decays

Probably the best reason for searching for family-number violating decays is because they are not there. Furthermore, physicists do not have any special reason why they are not, and they may be discovered at any time.

One of the great successes of modern particle physics is the Standard Model of electroweak interactions, $SU(3)_c \times SU(2)_W \times U(1)$. No experiment to date has demonstrated a convincing violation of its predictions. This model organizes all of the quarks and leptons into a kind of periodic table that contains three families. Despite its

successes, the model does not reveal the origin of the families or the reason why inter-family transitions are forbidden. Most physicists believe that the understanding of these mysteries will lead to new physics. The observation of the transitions would be an important clue as to the reason for the families.

Looking for the transitions via weak decays has a substantial advantage because the long lifetime of the particles gives a big factor in sensitivity. This idea is easily illustrated by comparing two simply related processes: $e^+e^- \to e^+\mu^-$ and $\mu^+ \to e^+e^+e^-$. Given an unknown coupling constant for the transition G_X, the ratio of the cross section for the annihilation to the branching ratio for the decay is approximately $G_X^2 s/(G_X^2/G_F^2) = sG_F^2$, where s is the center-of-mass collision energy and G_F the Fermi coupling constant. Our current limit for the decay is 10^{-12}, so that for a value of $s = 10^4$ GeV^2, the cross section for $e^+e^- \to e^+\mu^-$ is less than 4×10^{-46} cm^2. That is a value that would daunt even a neutrino physicist. At a luminosity of 10^{32}/cm^2-s, the event rate would be below 10^{-13}/s. The decay channel is favored by 10^6.

If a family violating decay is observed, it will not be because the standard neutrinos have a mass. For example, for the decay $\mu^+ \to e^+\gamma$, the branching ratio would be less than 10^{-20} even if the heaviest value of 30 MeV is assigned to the tau neutrino mass. Rather, the observation will be due to a more extensive modification of the Standard Model such as the existence of a new particle of very high mass.

For a variety of reasons, many theoretical physicist have proposed extensions to the Standard Model. These extensions include left-right symmetry, more Higgs doublets, gravity, compositeness of the existing elementary particles, horizontal gauges, supersymmetry, grand unification and so forth. All seem to introduce new particles of mass greater than 100 GeV, and unless explicitly removed, the new particles mediate family transitions. However, each model seems to favor certain decays over others, and it is necessary for the experiments to search in all reasonable places. A convenient way to organize the predictions is via the number of weak vertices required for the process to happen. Figure 1 demonstrates the point for the processes $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$ for two different extensions, a postulated very heavy neutrino or a horizontal gauge boson. In the top two diagrams, $\mu^+ \to e^+e^+e^-$ requires an extra weak interaction and is expected to be $\alpha/2\pi$ slower than $\mu^+ \to e^+\gamma$. However, if the new physics is a horizontal gauge boson, the situation is reversed. Normally, the lowest order diagram will have either two or three vertices, and as will be stated below, this has led to two distinct mass scales for new particles that are being probed.

Heavy Neutrino N

$\mu \rightarrow e\gamma$ — 3 Vertices

$\mu \rightarrow eee$ — 4 Vertices

Horizontal Gauge Boson Y^0

$\mu \rightarrow eee$ — 2 Vertices
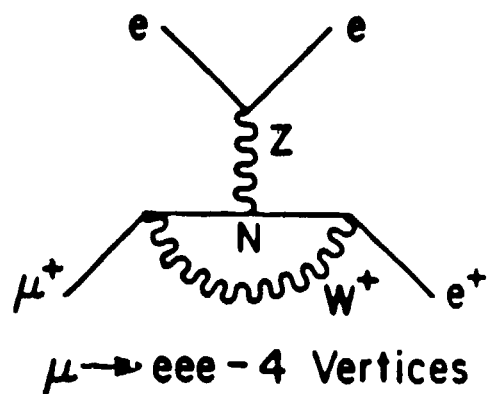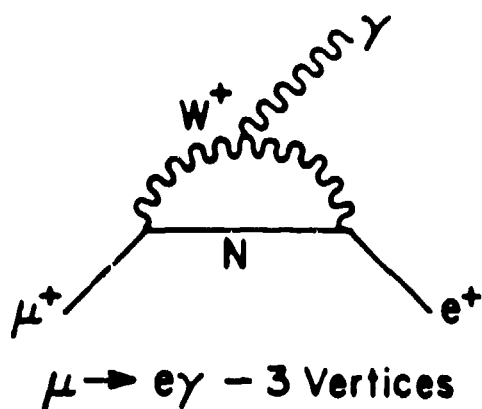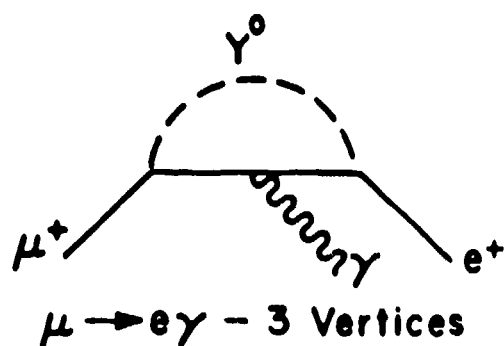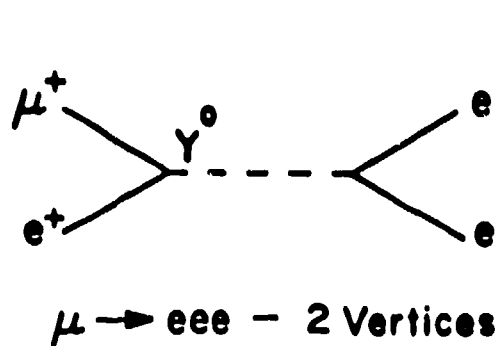
$\mu \rightarrow e\gamma$ — 3 Vertices

Fig. 1. Diagrams for inter-family transitions induced by either a heavy neutrino or a horizontal gauge boson. The comparison of $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ shows the number of weak vertices varies for different mechanisms.

A simple but important point can be made from the lower-left diagram in Fig. 1. If one calculates the rate for such a process, the propagator of the intermediate particle will introduce a term of the form $(q^2 + M^2)^{-2}$. As all these decays are for values of q^2 near zero, the rate will vary as M^{-4}. A little dimensional analysis will convince one that this dependence is general. Hence, these experiments are a hard way to proceed; it takes four orders-of-magnitude improvement in a branching ratio to search over one order of

magnitude in mass. Regardless of the difficulty, the experiments have done very well. In the field of rare muon decays, the limits on the branching ratio for $\mu^+ \to e^+\gamma$ has improved from 0.02 in 1948 to 5 x 10^{-11} in 1986, and 10^{-13} is within view. The rate of improvement rivals the rate at which beam energies in proton colliders has risen in the last 25 years even considering the M^{-4} factor.

As mentioned above, the current limits and future results from experiments in progress divide into two mass ranges of investigation according to the order of the process. Models involving left-right symmetry, horizontal gauge bosons, technicolor, and certain types of composite structures or Higgs particles are being searched in the 30-400 TeV region by the decays $K_L \to \mu e$, $K^+ \to \pi^+\mu e$, $\mu^+ \to e^+e^+e^-$ and $\mu^-A \to e^-A$. Models employing strings, supersymmetry, heavy neutrinos, and certain other types of composite structures or Higgs particles are being investigated at the 30-400 GeV mass scale by the decays $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+\gamma\gamma$, and $\mu^-A \to e^-A$. Searching for such heavy masses is analogous to discovering beta decay without any knowledge of the W boson.

As a closing point, rates are not the only possible observable. As soon as one of these decays is observed, the others will receive redoubled effort. The combined knowledge of the relative sizes of the decays will allow the underlying mechanism to be isolated. Additionally, if a decay is observed, one can look for other properties such as the asymmetry. For example, the $\mu^+ \to e^+\gamma$ decay has an asymmetry of the positron direction relative to the muon spin that will show up once there exist more than a few events. Most models predict the same cosine dependence as given by V - A, but the string model of Amowitt and Nath[2] gives an opposite asymmetry It will be very useful to be able to evaluate models for a given process according to all the easily observed properties of the decay.

3. Rare-Decay Experiments

There are ten principles that are almost always common to all rare-decay experiments:

1. The sought for process should have a clean experimental signature.
2. A large number of decays must be studied.
3. The detector must have large solid angle.
4. The detector must have high efficiency.
5. The detector must have high rate capability.
6. The detector must have sufficient resolution to suppress all backgrounds.
7. There must be a clever trigger.

8. The detector should measure a known process to prove it works.

9. The detector needs to be calibrated.

10. There needs to be a good Monte-Carlo simulation of the response of the detector.

In the following, these points will be illustrated for the MEGA experiment at LAMPF.

The experimental signature (point #1) for the $\mu^+ \rightarrow e^+\gamma$ decay from a stopped muon is a positron and a gamma ray that are back-to-back, each of 52.8 MeV, and originate from a common location in time coincidence. This signature is purely kinematic and has no dependence on the nature of the interaction causing the decay.

There are two possible backgrounds: one is the allowed decay $\mu^+ \rightarrow e^+\gamma\nu\nu$, and the other is the random coincidence between a high-energy positron from normal muon decay and a high-energy photon from another source that happens to satisfy the kinematic conditions. Both may be eliminated with a detector of good resolution in the measured characteristics of the decays. The MEGA experiment has been designed for resolutions that make it 20,000 times better at suppressing backgrounds (point #6) than the previous search[3] for the decay. All this is accomplished with good solid angle and 50-fold increased rate capability (points #3,#4 and #5). As a result, the experiment is background free, and the branching-ratio sensitivity improves linearly with the running time of the experiment, as opposed to the inverse square root of the running time if backgrounds were present.

The detector is illustrated in Fig. 2. It is contained in a solenoidal magnet that produces a magnetic field along the axis of the experiment. The field confines the positrons to the central region of the detector where a spectrometer consisting of wire chambers and scintillators measures their properties. Concentric with but outside the positron spectrometer are four pair-spectrometers for measuring the properties of the photons.

The detector has been described elsewhere[4]. In brief, to have the required rate capability, the wire chambers are of a very special design. They are of balloon construction with a normal thickness of 3×10^{-4} radiation lengths and employ the fast gas CF_4. They must work with greater than 10^4 particle crossings /mm^2-s (point #5). They are probably the best example of a detector that must work in an environment such as will be experienced at the SSC. To date, preliminary data have been taken with these detectors that agree quite well with the simulations (point #10). The pair spectrometers are also of novel construction and will be the largest of their kind ever built.

The rapidly falling characteristic of the photon spectrum makes it sufficient to trigger the apparatus for electronic readout whenever there is a photon above 37 MeV (point #7), and this criterion can be identified by programmable array logic. The data are then

converted to a digital format and stored in FASTBUS modules until the end of the beam burst. Next it is shipped to a microprocessor farm for further filtration before it is stored for final data analysis.
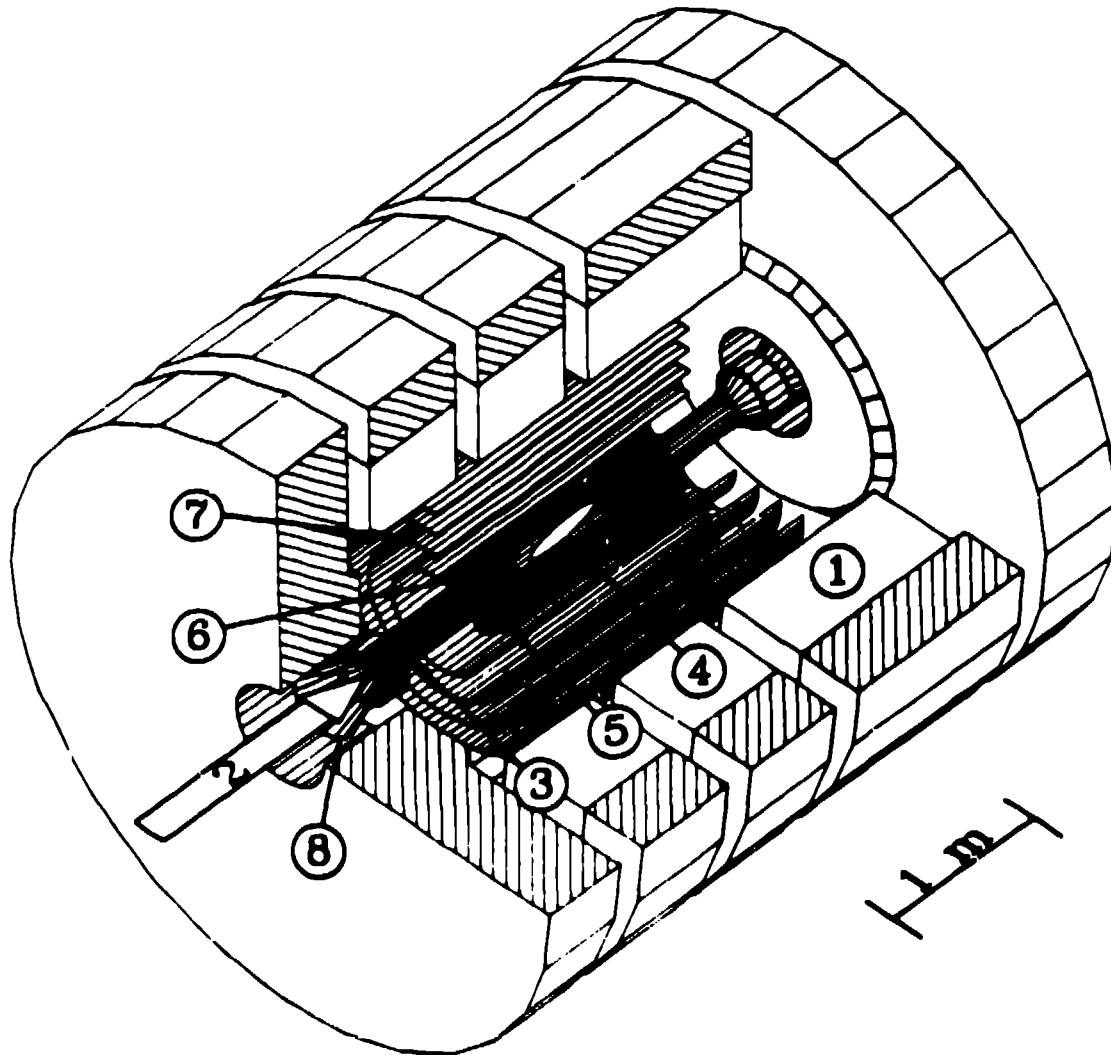
Fig. 2. A cutaway view of the MEGA apparatus. 1) The solenoidal magnet. 2) The beam 3) Beam line shielding and positron dump 4) The muon-stopping target 5) The positron wire chambers 6) The positron scintillators 7) The photon pair spectrometers 8) Veto counters.

Subsidiary measurements are made of the $\pi^- p \to \pi^0 n \to \gamma\gamma n$ reaction to calibrate the detector with 55- and 83-MeV photons (point #9). The positron arm is calibrated by showing the expected Michel spectrum for normal muon decay. Before it is complete,

more than 10^{13} muon decays will be examined (point #2). If no candidate satisfying the full criteria for $\mu^+ \rightarrow e^+\gamma$ is found, a limit for the branching ratio near 10^{-13} will be set. The result will be substantiated by showing that the detector observed the expected number of $\mu^+ \rightarrow e^+\gamma\nu\nu$ events when the criteria are loosened (point #8).

The schedule calls for the detector to be partly completed by 1992 and a sensitivity of 10^{-12} to be obtained. The final results should be available after 1993 and 1994 running. Below, the status of many such experiments will be summarized briefly, but a more careful examination of each would reveal that most or all of the above points are relevant to their design and execution.

4. Survey of Current Results and Experiments

Essentially every laboratory in the world that can work in this field has contributed to the results. The present limit[3] on the branching ratio $\Gamma(\mu^+ \rightarrow e^+\gamma)/\Gamma(\mu^+ \rightarrow all) < 5.0 \times 10^{-11}$ comes from LAMPF. The MEGA experiment discussed above will improve on those results by more than two orders of magnitude.

Using a time projection chamber, scientists at TRIUMF have established limits[5] cn the processes $\Gamma(\mu^-Ti \rightarrow e^-Ti)/\Gamma(\mu^-Ti\ Capture) < 4.6 \times 10^{-12}$ and $\Gamma(\mu^-Ti \rightarrow e^+Ti)/\Gamma(\mu^-Ti\ Capture) < 1.7 \times 10^{-10}$.

At the Paul Scherrer Institute, the SINDRUM I detector, a solenoid filled with cylindrical wire chambers and scintillator arrays, has measured the branching ratio[6] $\Gamma(\mu^+ \rightarrow e^+e^+e^-)/\Gamma(\mu^+ \rightarrow e^+\nu\nu) < 1.0 \times 10^{-12}$. They are building a new detector (SINDRUM II) and beam line for the purpose of measuring muon-electron conversion that has already yielded the result[7] $\Gamma(\mu^-Ti \rightarrow e^-Ti)/\Gamma(\mu^-Ti\ Capture) < 4.4 \times 10^{-12}$. When a new trap for producing high-intensity μ^--beams without pions becomes available, the design predicts a possible sensitivity of 3×10^{-14}.

The Institute for Nuclear Structure is still building their muon factory near Moscow. They have very ambitious plans to push the limit on muon-electron conversion[8]. They will incorporate the pion-production target into the experiment to get three orders of magnitude more muon flux by surrounding the primary proton beam with a superconducting solenoid. The novel design has the potential for an unprecedented sensitivity in the 10^{-15} to 10^{-16} range.

Another interesting process, though not a rare decay, is muonium-antimuonium conversion. It is unique amongst the flavor-changing process by converting the flavor of both the muon and electron by two units of family number. The results are quoted in terms

of the strength of the coupling constant. The current limit[9] comes from LAMPF and is $G_{M\bar{M}} < 0.16\ G_F$. Making use of the SINDRUM I detector, a new experiment[10] hopes for sensitivity of $G_{M\bar{M}} < 10^{-3}\ G_F$.

In the absence of a kaon factory, almost all information on the rare-decays of kaons comes from Brookhaven and KEK. The current limit[11] on $\Gamma(K^+ \to \pi^+\mu e)/\Gamma(K^+ \to \text{all}) < 2.1 \times 10^{-10}$, and a new effort is being mounted with a sensitivity of 5×10^{-12}. The best limit[12] on neutral kaon decays is $\Gamma(K_L \to \mu e)/\Gamma(K_L \to \text{all}) < 8.5 \times 10^{-11}$. However, the same group has already taken data with a sensitivity down to 10^{-11}, and has proposed a new experiment with another order of magnitude improvement.

A selected subset of rare-tau-decay branching ratios taken from the particle data book[13] are:

$\Gamma(\tau \to \mu\gamma)/\Gamma(\tau \to \text{all})$	$< 5.5 \times 10^{-4}$
$\Gamma(\tau \to e\gamma)/\Gamma(\tau \to \text{all})$	$< 2.0 \times 10^{-4}$
$\Gamma(\tau \to \mu\mu\mu)/\Gamma(\tau \to \text{all})$	$< 2.9 \times 10^{-5}$
$\Gamma(\tau \to \mu\mu e)/\Gamma(\tau \to \text{all})$	$< 3.3 \times 10^{-5}$
$\Gamma(\tau \to \mu ee)/\Gamma(\tau \to \text{all})$	$< 3.3 \times 10^{-5}$
$\Gamma(\tau \to eee)/\Gamma(\tau \to \text{all})$	$< 3.8 \times 10^{-5}$

These numbers do not challenge the Standard Model at the same level as the rare muon and kaon decays because of the following argument. Compare the branching ratio for $\tau \to e\gamma$ to $\mu \to e\gamma$. The ratio is $[\Gamma(\tau \to e\gamma)/\Gamma(\tau \to \text{all})]/[\Gamma(\mu \to e\gamma)/\Gamma(\mu \to \text{all})] = [\Gamma(\tau \to e\gamma)/[\Gamma(\mu \to e\gamma)] \cdot \tau_\tau/\tau_\mu = (m_\tau/m_\mu)^5 \cdot f(\text{mixing angles}) \cdot \tau_\tau/\tau_\mu = 0.19 \cdot f(\text{mixing angles})$. The function of mixing angles is unlikely to be more than a couple of orders of magnitude different from 1, so the current limit on $\mu \to e\gamma$ is a much more severe constraint on the $\tau \to e\gamma$ branching ratio than the experiments assuming there is no special physics that unnaturally enhances the tau decays.

5. Conclusions

Searching for family violating decays is an active field of experimental endeavor. The next few years promise one to three orders-of-magnitude improvement in many of the limits. If one believes the probability density for discovery is flat in the exponent of the branching ratio, one can assess the chances for seeing one of these processes in the next decade. A pessimist would say it can be anywhere from the current limits to that induced by very low-mass neutrinos, say 10^{-40}; then the chances are less than 10%. An optimist would say that inter-family transitions are due to new particles of less than 1 TeV in mass,

e.g. produced by supersymmetry or string models; then the branching ratios are likely to be greater than 10^{-16} and the chances are indeed good, perhaps 50%.

6. References

*Work supported by the U.S. Department of Energy

1. Current collaboration members: D. Barlow, B. M. K. Nefkens, B. Tippens, J. Crocker, S. C. Wright, P. S Cooper, M. Barakat, M. Dzemidzic, J. Flick, E. V. Hungerford III, K. Lan, B. W. Mayes II, L. Pinsky, L. Tang, W. von Witsch, J. Szymanski, J. F. Amann, K. Black, R. D. Bolton, S. Carius, M. D. Cooper , W. Foreman, R. Harrison, G. Hart, N. Hoffman, G. E. Hogan, N. June, D. Kercher, T. Kozlowski, R. E. Mischke, F. J. Naivar, J. Novak, M. A. Oothoudt, C. Pillai, S. Schilling, S. Stanislaus, J. Sturrock, D. Whitehouse, A. Hallin, E. B. Hughes, C. Jui, J. N. Otis, C. Gagliardi, G. Kim, F. Liu, R. E. Tribble, L. Van Ausdeln, R. J. Fisk, D. D. Koetke, R. Manweiler, W. Stephens, B. Wright, K. O. H. Ziock, L. E. Piilonen, and J. K. Markey, *LAMPF proposal* **969** (1985).

2. R. Arnowitt and P. Nath, *Phys. Rev. Lett.* **66** (1991) 2708.

3. R. D. Bolton, M. D. Cooper, J. S. Frank, A. L. Hallin, P. A. Heusi, C. M. Hoffman, G. E. Hogan, F. G. Mariam, H. S. Matis, R. E. Mischke, L. E. Piilonen, V. D. Sandberg, G. H. Sanders, U. Sennhauser, R. Werbeck, R. A. Williams, S. L. Wilson, R. Hofstadter, E. B. Hughes, M. W. Ritter, D. Grosnick, S. C. Wright, V. L. Highland, and J. McDonough, *Phys. Rev.* **D38** (1988) 2077.

4. M. D. Cooper, Intersections Between Particle and Nuclear Physics, Rockport, Maine, *AIP Confererence Proceedings* **176** (1988) 845.

5. S. Ahmad, G. Azuelos, M. Blecher, D. A. Bryman, R. A. Burnham, E. T. H. Clifford, P. Depommier, M. S. Dixit, K. Gotow, C. K. Hargrove, M. Hasinoff, M. Leitch, J. A. Macdonald, H. Mes, I. Navon, T. Numao, J-M. Poutissou, R. Poutissou, P. Schlatter, J. Spuller, and J. Summhammer, *Phys. Rev.* **D38** (1988) 2102.

6. U. Bellgardt, G. Otter, R. Eichler, L. Felawka, C. Niebuhr, H. K. Walter, W. Bertl, N. Lordong, J. Martino, S. Egli, R. Engfer, Ch. Grab, M. Grossmann-Handschin, E. A. Hermes, N. Kraus, F. Muheim, H. Pruys, A. van der Schaaf, and D. Vermuelen, *Nucl. Phys.* **B299** (1988) 1

7. J Bagaturia, W. Bertl, C. Dohmen, W. Dzhordzhadze, J. Egger, R. Engfer, Ch. Findeisen, M. Grossmann-Handschin, K.-D. Groth, E. A. Hermes, W. Herold, J.

Hofmann, W. Honecker, T. Kozlowski, B. Krause, G. Melitauri, A. Mtchedlishvili, F. Muheim, U. Muller, C. B. Niebuhr, G. Otter, S. Playfer, H. S. Pruys, D. Renker, L. Richen, A. van der Schaaf, O, Szavits, D. Vermeulen, H. K. Walter, and P. Wintz, PSI *Nucl. and Part. Phys. Newsletter* (January 1991) 30.

8. A. I. Bochkarev, R. M. Dzhilkibaev, and V. M. Lobashev, *Ins. Nucl. Struct. (Moscow) Preprint* **P-0575** (1988).

9. B. E. Matthias, Ph. D. Thesis, Yale University (1991); H.-J. Mundinger, H. Ahn, F. Chmely, M. Eckhause, V. W. Hughes, K. P. Jungmann, J. R. Kane, S. H. Kettell, Y. Kuang, B. E. Matthias, B. Ni, G. zu Putlitz, H. R. Schaefer, and K. A. Woodle, Rare Decay Symposium, Vancouver, B. C., Canada (World Scientific, 1988) 434

10. K. Jungmann, B. E. Matthias, H.-J. Mundinger, J. Rosenkranz, W. Schafer, W. Schwarz, G. zu Putlitz, D. Ciskowski, V. W. Hughes, R. Engfer, E. A. Hermes, C. Niebuhr, H. S. Pruys, R. Abela, A. Badertscher, W. Bertl, D. Renker, H. K. Walter, D. Kampmann, G. Otter, R. Seeliger, T. Kozlowski, and S. Korentschenko, *PSI Proposal* **89-06.1** (1989)

11. A. M. Lee, C. Alliegro, C. Campagnari, V. Chaloupa, P. S. Cooper, J. Egger, H. A. Gordon, N. J. Hadley, W. D. Herold, E. A. Jagel, H. Kaspar, D. M. Lazarus, H. J. Lubatti, P. Rehak, M. E. Zeller, and T. Zhao, *Phys. Rev. Lett.* **64** (1990) 165.

12. W. R. Molson, *Proc. of A Workshop on Science at the KAON Factory,* TRIUMF, Vancouver, B.C., Canada (1990); T. Inagaki, M. Kobayashi, T. Sato, T. Shinkawa, F. Suekane, K. Takamatsu, Y. Yoshimura, K. Ishikawa, T. Kishida, T. K. Komatsubara, M. Kuze, F. Sai, J. Tojoura, S. S. Yamamoto, and Y. Hemmi, *Phys. Rev.* **D40** (1989) 1712.

13. Particle Data Group, *Phys. Lett.* **B239** (1990).